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DISSERTATION...

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September 10, 2016

Contents

1 Introduction

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Autonomous cars are currently a topic of great interest. Around the world the biggest private companies or government's initiatives are developing self-driving vehicles (uber, google, britol car citations), competing for new emerging market. Each company focuses efforts in different direction. The companies are either trying to develope an all-round car that could perform in both city and on highways or restrict the usage to particular types of roads (tesla). Or anyhing in between. The most significant commercial initiatives include Google driverless car, Tesla, Uber (). Goverment founded initiatives include Venturer and ...

- Background of the problem, context of the research, reasons why the study was carried out, significance of the study

Many experts around the world are trying to predict how autonomous cars will influence our lives. One of the questions is how the traffic itself will change. Most of the experts agree that in the next decades we will observe gradual process of increasing the share of autonomous cars on our roads. In that time human-driven cars and self driving cars will have to successfully interact with each other. According to predictions the fully automated traffic will become reality only around year 2060 or year 2040 in more optimistic predictions and first commercial autonomous cars are already appearing on the roads (singapore, uber). Although there are numerous studies on many aspect of autonomous driving as well as on interactions between regular cars in all-human-traffic there is little research on interactions between these two types of vehicles and all it's consequences.

- A statement of the problem to be addressed

reflect on original Eddie's idea

The focus of this research is to investigate how autonomous cars will influence traffic itself and how human and autonomous cars will interact with each other.

- clear and succinct statement of research questions, aims and objectives.

The main aim of the research was trying to predict what will happen when autonomous cars are introduced to traditional traffic. Results obtained were analysed from the point of view to traffic parameters such as velocities, densities, congestion and from the point of view how individual drivers reacted differently when autonomous vehicle was encountered.

The main objective of the project was to conduct experiments with human drivers and autonomous cars. In the center of the project was a network-based, multi player traffic simulation. Each person participating in the experiment controlled one vehicle and made decisions by observing other traffic participants. By looking into how cars interact with each other it should be possible to extract the impact of self-driving vehicles on the traffic.

The main objective of the project was to create a an on-line traffic simulation that would allow to connect multiple people together at the same time. People were asked to drive a car

How scope was reduced The original scope of the project included also in-robotico implementation that would be using remotely controlled ”slot-cars” to simulate traffic. It was believed that physical model would have features that could not be accounted for or predicted in computer simulation. It was estimated for around 50% of implementation effort. However, in the final version of the project the physical model was not implemented. After the project went into development the advantages of creating a physical model appeared less and less attractive. Especially compared to the cost of implementation. Original idea assumed using digital slot-car set with cars and track, as well as computer vision to track vehicles on the track and live video streaming to multiple computers. After more careful consideration the benefits of implementing above described would be very minor or none. In addition to this, implementing the computer simulation consumed more time that estimated.

It has to be admitted that scope was drastically limited in terms of implementation effort. It did not, however, have much impact on the quality of the research and conclusions. One would even venture to say that project should only consist of computer simulation even if more time and resources were allowed for project execution.

A road map of what is going to be discussed The project consisted of three main parts. First one was software development. This accounted for around 50% of all efforts. The chapter on Research Methodology is mostly dedicated to this. Software section is divided into most significant components that include the design of simulation master, design of client's interface and vehicle's control. The chapter on research methodology also describes how communication between machines was established and the algorithm behind autonomous vehicles. Although these two aspects were integral parts of the software it was decided to write about them separately due to the significance and universality of communication solution and autonomous car algorithm. Most of decisions made throughout the development stage were aimed for successful experiment execution. The design of the experiment is described at the of Research Methodology chapter. The description of how the experiment was eventually conducted is placed at the begging of Finding and results chapter.

The Research Methodology chapter is preceded with in-depth chapter describing literature relevant to the project. The data obtained during the experiment was described in Findings and Results chapter. This chapter also talks about different ways in which data was analysed. The last two closing chapters discuss the results of the experiment, attempt to draw conclusions and generalize findings in wider context.

2 Literature review

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There is plenty of literature dedicated to autonomous cars.

2.1 Current and future development of autonomous cars

The prime examples of the most recent achievements in the field of autonomous cars are visible through cutting-edge commercial projects such as google self driving car, uber's and <shanghai something>. Google is probably the most experienced player as it's self driving car project started already in the year 2009 (google self driving car website). Google's car is classified as level 3 in automated vehicle classification system proposed by NHTSA in 2013 (http://www.nhtsa.gov/About+NHTSA/Press+Releases/U.S.+Department+of+Transporta which is described as ”Limited Self-Driving Automation”. The car takes full control over all safety-critical functions but at certain times driver can be asked to retake control.

List of trials on autonomous vehicles is here: (Parkin et al. 2016) googel, volvo, audi, singapore, and add uber

More and more commercially available vehicles feature level 2 of autonomy and are capable of emergency braking, lane control or adaptive cruise control. Even more advanced cars, like Tesla S are able to actively change lanes on a motorway when instructed by driver(link to tesla's manual).

Vehicle classified at level 4 would have to

Uber is a relatively new player in the business of autonomous cars.

Write about audi autonomous racing car

In the near future we should be able to see more and more autonomous vehicles on the roads. The report released by UK Department of Transport titled ”The Pathway to Driverless Cars Summary report and action plan” (UK Department of Transport 2015) states that government recognises the benefits of autonomous vehicles and is undertaking actions to aid the development of technologies and law that would allow to bring driverless cars on public roads.

2.2 Implications of autonomous cars revolution

Experts around the world argue about the consequences of introducing self-driving cars. The report by UK Department of Transport ”The Pathway to Driverless Cars” summarizes some main benefits of heaving autonomous cars. Most important points include significant reduction of time spent in vehicles and largely improved safety. It is stayed that an average driver could save up to 6 working weeks of driving time in a single year. A claim on potential safety improvements is backed by existing evidence from automated vehicles that are already commercially available and feature level 2 autonomy. Another important benefits include reduced emission and reduced congestion. Vehicles that are connected into one system would be able to drive in the interest of all traffic participants and therefore greatly optimize traffic. A consequence of traffic optimization and overall reduction of Total Kilometers Traveled would be major cost reduction and the result could be increased access to vehicles for everyone(UK Department of Transport 2015).

On the other hand, it is argued that autonomous vehicles will not be as robust as expected and traffic parameters will, in fact, worsen(Sivak & Schoettle 2015).

There are also many other indirect implications. As stated in (Litman 2014) an example will be a family that decides to settle further from the city because they can spend time in the car productively rather than controlling the vehicle. In consequence the benefits of faster and more optimized travel will be counteracted by overall increase in road demand. Consecutively the traffic parameters may not improve as expected.

Rely heavily on: (Litman 2014)

adittionally:

2.3 Maximum Capacity Theorem

Traffic has an ability to self organize close to its capacity. This rule called Fundamental Law of Traffic Congestion or Maximum Capacity Theorem states that when stock of available roads rises, the overall driving increases too (Duranton & Turner 2011). The theory behind it explains why building new roads or adding new lanes does not necessary yield proportional decrease in congestion.

Duranton and Turner identified four major sources of additional traffic such as increased commercial traffic, alteration to individual driving behaviour, population growth and diversion from other roads. Raised availability of roads cause an increase in Vehicle Kilometres Travelled(VKT) by commercial vehicles as well as private commuters. Choosing a car as a mean of transport will appear as a more attractive option.

This theorem could be put in the context of autonomous vehicles. As mentioned before, introducing autonomous cars to the traffic should result in reduced congestion as travelling would be more optimized. However, according to the Fundamental Law of Traffic Congestion, less traffic on the roads can encourage people to travel more. Consequently this will rise overall road demand and the traffic will reach it's new capacity.

2.4 Conflicts, collisions and interactions on the road

(Parkin et al. 2016)

According to (Contributory factors of reported accidents, Great Britain excel) most accidents are caused by human failure. The main contributory factors are failure to look properly, failure to judge other's person speed or path and driver, carelessness, recklessness or being in a hurry.

(writing about it in the context that autonomous cars can potentially improve these things)

Although the study on conflicts on the road is very complex and hard to quantify according to (Risser 1985) there are numerous factors that contribute to creating conflicts. These factors include excessive speed or poorly adopted speed, too small distance to proceeding car, violations of the right-of-way and many other types of behaviour.

More about interactions in general...

2.5 How people will cooperate with autonomous cars

In the next decades driverless cars will be required to succesfully cooperate with human drivers. Even when all cars become autonomous , pedestrians, cyclists and other traffic participants must still be able to move around. Human driver have certain expectations from other drivers. Things like eye-contact are often important for succesful communication. That kind of interaction will be absent in encounters with autonomous vehicles. Moreover, drivers often posses skills and experience that may not be easy to quantify and program into machine. Therefore driverless cars can, in fact, perform worse in certain situations(Sivak & Schoettle 2015). During transition period the amount of accident can in fact increase.

As mentioned in introducing autonomous cars should result in smaller number of accidents. A machine would be free from factors mentioned in previous chapter.

2.6 Measuring traffic parameters

In order to evaluate traffic performance four key parameters will be measured as suggested in a paper by Beymer and McLauchlan (Beymer et al. 1997).

- Flow - Amount of vehicles in one hour (will be separately evaluated for different parts of the track)
- Velocity - Average velocity of individual car or multiple cars
- Density - Amount of vehicles in for specified distance

- Headway - Spacing between vehicles

Additionally to the parameters above the traffic will be analysed in terms of amount of accidents.

2.7 Modelling car behavior

write about the model in sumo

write how it applied to both human and autonomous

write about possible models of car's behaviours

Inteligent driver model etc

gipps

2.8 SUMO

SUMO stands for Simulation of Urban MObility. It's an open source framework used for traffic simulation(Krajzewicz et al. 2002). SUMO was first introduced in 2002 and since then it became a popular tool for scientist as well as people involved in practical traffic planning tasks.

SUMO is a purely microscopic simulation which means every traffic participant is modelled separately. The framework is designed to simulate large cities that contain thousands of roads and more than one million of vehicles.

The core of the SUMO package is a logical representation of road layout. Segments of roads separated by junctions are described as nodes and edges. Edges consist of directed lanes. Vehicle's position is described in terms of edge and lane number and distance from origin node. At every step of the simulation interaction between individual simulation entities are computed and all parameters updated. (Krajzewicz et al. 2002)

SUMO is supported by additional pieces of software such as a tool for importing map structure and a plug-in for providing on-line inputs.

The applications of SUMO include designing traffic light sequence, predicting demands on planned roads or creating traffic control systems.

It is a microscopic

It allows to account for multiple factors to create

quick summary of sumo

2.9 Communication between machines - maybe

2.10 Experiment design - real world research

Parkin et al. (2016)

3 Research Methodology

The main aim of the project was to look into interactions between autonomous and human-driven vehicles. The main method that was used to achieve this was to create a simulation of traffic with both types of traffic participants. By reviewing the literature it was found that there are numerous car-following models that could be used as a model of human driver. However, no matter how good were these models, they could only work as an approximation of how humans would actually control the cars. It was decided that differences between any of the reviewed car-following algorithms and real human control are so significant that the study should rely on the experiment involving multiple human participants controlling cars in interconnected, on-line simulation.

The decision to create such a simulation was a key factor that gave shape to the whole project and accounted for the majority of the time spent on it.

end here...?

The consequence of heaving an experiment that involved multiple participants was that the major effort was put into developing software that would allow to conduct the experiment. Implementing the simulation was the most significant factor accounting for the complexity of the project.

Justify the structure of the project. Why the experiment was a key part. Why this was the best option rather than for example use data from some database?...hmmm

3.1 Experiment design

***add sth about qualitive/quantive method!

The experiment was arguably the most important part of the project. All work done before was aimed at successful conductance of the experiment and all work done after was based on the data collected during the experiment.

style note: *This is all written in conditional because it was a plan and actual implementation is a different story??*

The experiment was planned to involve ten to twenty people. They would be asked to control one of the vehicles in the simulation. Each of them would sit in front of a computer where they could use keyboard and observe the screen. On the screen they would see a top down view of their own vehicle and it's surrounding. By using the keyboard they would control the acceleration of their vehicle. The instructions given would encourage them to explore the map and avoid collisions with other traffic participants.

The experiment was planned to consist of three main sessions and one learning session. Each session would feature different scenario which determines road layout, number of human-driven cars and number of autonomous cars. During learning session participants would learn(change this word) how to control the car, how car responds to their commands,how to turn and what the environment looked like. After learning period the first phase would commence and second afterwards. Both phases would use identical map but the proportion of traditional cars to autonomous would change. The map shape would be an infinity-sign-like where vehicles would have to follow each other and there would be one intersection. It was assumed that such an approach would allow to measure macro parameters of the traffic as both phases would be comparable and the impact of autonomous vehicles could be extracted. The initial choice of measured parameters would include average velocity, density, flow and headway. The scenario in the third phase would use significantly more complex map with 3-way intersections, road exits and road accesses(this sounds wrong?). It would feature a similar number of human-driven and autonomous cars. The focus of the analysis would be microscopic interaction between cars in various road situations. Number of autonomous vehicles driving on the map depended on the number of people turning up for the experiment. Additionally map used for phase one and two could be scaled according to the total number of cars.

The instructions given to experiment participants before each phase stated the following:

1. Cover as long distance as possible
2. Avoid collisions with other cars at all cost
3. Use key described below to control the car

4. When given a choice to turn at the intersection it's your decision which direction you want to go
5. Listen to other instructions

At every frame of the simulation all necessary data was recorded for further analysis. In the event of collision the cars would be allowed to pass through each other. Naturally the event was recorded and collision alert was displayed for drivers involved in the accident. Collisions were unwanted events that were considered a distortions affecting the results. By allowing the cars to pass, the traffic disturbance was mitigated. Another considered ideas such as teleporting vehicles to another place or manually changing the velocities would have greater impact on traffic smoothness.

The algorithm for the autonomous car was based on Intelligent Driver Model. It is discussed in detail in Software development section. The velocity for autonomous vehicles was capped at 10 m-s but the acceleration was faster than traditional cars.

(a screenshot from the client gui . Say about control key described, speedometer and collision alert.)

3.1.1 Client's interface

The main aim of the graphical interface was to mimic what a person driving a car would actually see from the inside of his or her vehicle. Compared to what a driver sees in real world the representation of the environment had to largely simplified. The challenge was to preserve as much of the realism as possible keeping in mind the main principles of the experiment. The cars were represented as coloured rectangles 2 meters wide and 4.5 meters long. Driver's vehicle was always position in the middle of the screen while map and other vehicles were moving around it. Roads were X? meters wide, coloured in black with red boundaries. Each track was overlaid on graphical background with many distinctive features to allow for better sensation of speed.(reference to website

Car control using keyboard First things to decide on was how the car was controlled. Fundamentally the car had one degree of freedom as it always went along a predefined path. Only in the event of road split the driver could make discreet choice on which direction to go. The acceleration of the car was controlled by A and Z keys. Pressing A made car accelerate with a value calculated from Gipps' car following model discussed in later section. The maximum velocity was capped at 15m-s. Pressing Z key applied constant deceleration of -6.5 m-s2. Additionally drivers could press space bar which functioned as a hand break and applied deceleration of -10 m-s2. These number were found empirically so that car responded realistically (add:? in the subjective opinion of three people). Backward movement was disabled for greater simplification(??). The reason for not using arrow keys was that arrow key were used to control car's turn direction. Some intersections featured choice between straight, left and right turn.

Size of view field Another design decision concerned the size of driver's view field. The shape and size of the view field was a square 80 meters by 80 meters where car was positioned 20 meters from the bottom as it is showed on figure(number). It was assumed that for a driver travelling at full speed it should be possible to comfortably slow down to zero when a stationary vehicle suddenly appears in front of it. The amount of time elapsing from first sight of the obstacle to coming to full stop includes reaction time and breaking time. According to (Summala et al. 1998) average reaction time for a vehicle without brake lights is about 2 seconds which corresponds to 30 meters travelled. Breaking at -6.5 m-s2 from 15 m-s takes 2.3 seconds which consequently corresponds to 17.2 meters. So the minimal distance that driver should be able to see ahead is 47.2 meters. After initial tests this lower-bound value proved to be too small and after few other trials was extended to 60 meters. Another 20 meters of sight distance was added behind the car.

(only viewport image)

3.1.2 Scenarios

Each scenario specifies configuration of the map, number of human drivers, number of autonomous cars, initial position of each car and length of the simulation. While map configuration had to be prepared before, number of vehicles of each type and time of the simulation could be set at the start of the experiment. This flexibility helped to accommodate for unknown number of people that showed up for the experiment. To ensure reasonable congestion but yet high number of interactions each map was intended for different number of vehicles. A benchmark test with solely autonomous cars and additional empirical tests allowed to establish that every vehicle should correspond to 45 to

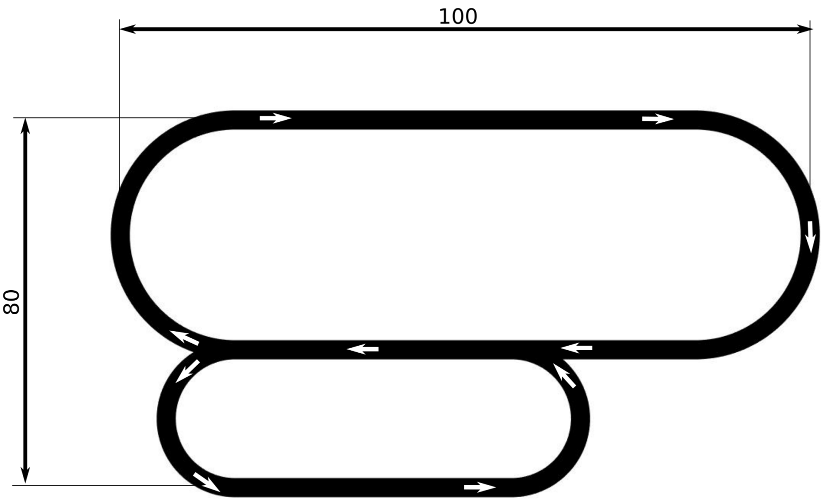

Figure 1: Map used in learning scenario. It featured one road exit and one road split. Dimensions are given in meters.

80 meters of total track length.

In all scenarios participants were not told which car is autonomous and which is controlled by another human. They could, however try to guess the type of the car from how it behaved.

Learning phase

(*here im actually talking about using all participants while in fact they were splited into two groups.. . that information would be revealed later in experiment execution chapter*)

The learning period involved all participants and one autonomous car. It lasted 2 to 3 minutes and was intended for getting familiar with the simulation. The data from this period was recorded but was not intended for analysis. In that period participants could ask additional questions. The map used in this scenario is presented on Figure 1.

Scenario 1

In the first scenario all participants were involved and there was one autonomous car. The map featured figure of eight shape as showed on Figure 2. The intersection in the middle was uncontrolled as it did not have any priority rule. It was hoped that this way cars would

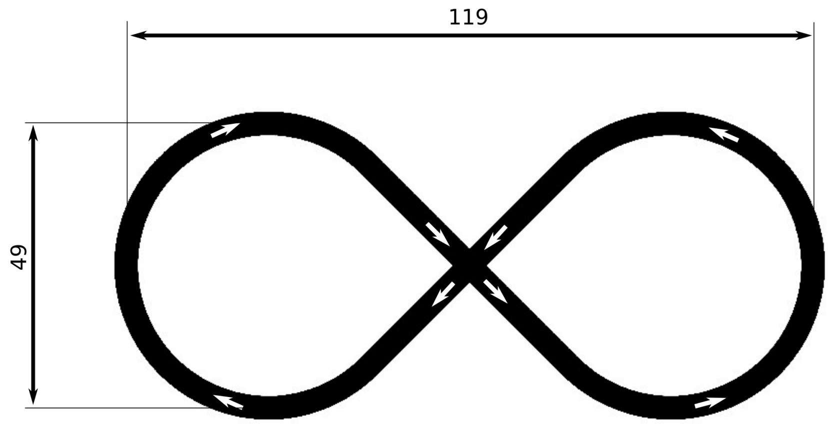

Figure 2: Map used in First and Second scenario. It featured figure of eight shape. There were no road splits and cars had to follow each other. Dimensions are given in meters. Covering the whole map at full speed of 15m-s would take 22 seconds. The track was intended for 6 to 10 vehicles.

face uncertain situations and interactions will be more vibrant. This scenario was intended to capture interactions in traffic consisting almost entirely of traditional cars. Interactions were either between cars following each other or between cars at the intersection. It was hoped to observe how people are keeping distance to car ahead, how conflicts at intersection are resolved and what are the potential queueing behaviours. One autonomous car was added because(why it was added??). Before the simulation started, participants were briefed what is the shape of the map but they were not told how many autonomous cars were in the simulation. This phase was planned to last 4 to 8 minutes depending on the number of participants.

Scenario 2

In scenario 2 around 35% of people taking part in the first scenario was substituted for autonomous cars. This scenario used identical map as scenario 1 (Figure 2) and total number of cars didn't change. It was hoped that this way the results will be comparable to first scenario. Particular interest was in the interactions at the intersection. The autonomous cars were always letting human-driven cars go first if collision was anticipated. The humans however didn't know which car is what type and communication happened only via observation of each other's movement.

Similar to previous scenario the planned length would range between 4 and 8 minutes.

Scenario 3

Scenario 3 aimed at microscopic interaction between particular groups of vehicles. The map used in this scenario featured multiple types of intersections and was much more complex than previous one as it is shown on figure 3. The amount of human-controlled cars was equal to the number of autonomous cars. The total density of all vehicles was twice lower than in previous scenarios but because of multiple intersections the number of interactions stayed high.

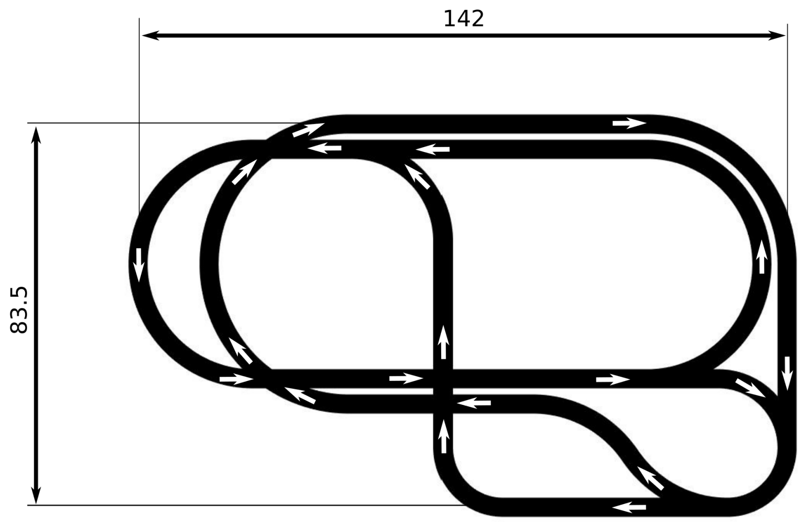

Figure 3: Map used in the third scenario. It featured 2 road splits where drivers could change direction, 2 diagonal intersections,a 3-way intersection and 2 road accesses(?). The total length of all segments was 875 m. Travelling at 15m-s it would take 59 seconds to cover that distance. This was the longest track in the experiment and was designed for 8 to 14 vehicles.

3.2 Software development

Creating software that allowed to successfully conduct the experiment was the longest and most absorbing part of the project. All decisions starting from the choice of programming environment, through deciding on the structure of the software to ensuring simulation reliability were dictated by the requirements of the experiment. From the point of view of software implementation the experiment required different applications running on multiple machines that would be talking to each other over the network in real-time.

The aim of the softwa

Scalability - although traffic was represented in a very simplified way, the goal was to identify the most important factors influencing

Reliability - software should be tested for different circumstances.

To ensure validity of the results some basic principles were followed throughout the whole process:

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//say about the aims of the software. what makes good software good? maybe look here:

//write more intro to software

say how this was not important o avoid cheating as described by Arthur earlier

Justify all major design decisions

Justify all major design decisions. Plenty of them! All the actions undertaken to ensure most meaningful results

3.2.1 Environment choice

Choosing the right environment to develop software was a key decision that had crucial impact on all components of the project. After a process of careful consideration it was decided to use MATLAB as a sole development environment for all parts of the project. The initial Project Proposal written by project supervisor, Eddie Wilson suggested using SUMO package as a core of the simulation. It was assumed that a small part of SUMO capabilities would be utilized in combinations with additional software written for the purpose of this project. SUMO features Traffic Control Interface (TraCI) (*link to website*) that gives access to running simulation. The parameters of the simulation like car's location could be potentially retrieved and manipulated in real-time. The additional software would be responsible for data exchange over the network, visualizing car's surrounding and capturing inputs from experiment participants. Most likely the programming language used for this part would be C++. On the other hand, SUMO was intended for much larger simulations than the one planned. Vast majority of available features would not be used and could rather be a source of potential issues.

A competing idea was to create a tailored application that would be inspired by the structure of SUMO but would be written from scratch. It would be implemented using C++ or MATLAB environment. The main benefit of this approach would be full control of the software behaviour. The main drawback would be rewriting algorithms and structure that already existed inside SUMO. In terms of subjective software preference MATLAB was considered most familiar and least error prone.

Another key question that had large impact on the decision was how to establish reliable communication between machines. It was found that MATLAB supports at least three possible ways of communication that could be used in the project including User Datagram Protocol (UDP), Transmission Control Protocol (TCPIP) and Robot Operating System. This was the main reason why MATLAB was eventually chose for this project. Details of the implementation of computer-to-computer communication are described in the chapter "Communication between machines".

3.2.2 Software architecture

(present tense here..?)

The software in the project consists of three main parts. The most important one is Simulation Server Application. It is responsible for all data processing that is essential for the simulation. The second piece of software is Simulation Client Application. Each participant used an identical copy of Simulation Client Application to receive information about car's surroundings and send acceleration and direction orders to the server. Last part of the software is Communication Agent which was responsible for aggregating information from all clients and sending it to the server. It's existence was dictated by the requirements of network solution described in further chapters. Server, Agent and all Clients' applications were running on separate machines.

Main part of the simulation was main loop that was executing at fixed rate of 16 Hz.

All machines used in experiment were synchronized according to Server's clock. The simplified sequence of events across all applications is described in Table 1.

3.2.3 Simulation Server Application design

Simulation Server Application was at the heart of the simulation. It was responsible for all essential computation, managing communication between other entities and executing code at at a fixed rate. Its design consisted of following classes (appendix: class diagram):

- Simulation - Only one object of this, essential class existed throughout entire simulation. The most important methods were accountable for establishing communication, importing parameters and running main simulation loop.
- Map - Single Map object was created by Simulation. Among other things it contained all information regarding road layout, references to all vehicles, relations between them and future predictions.
- Car - Base class intended to derive other classes from it. It contained features common for both types of vehicles such as velocity and distance calculations and Gipps model.
- Car human driven - Derived from Car class. It contained additional attributes specific to human-driver but only basic methods as most of essential computation was happening within Map class.
- Car autonomous - The Intelligent Driver Model and decision making algorithm were encapsulated within this class. It was receiving limited information about car surrounding from Map object.
- Participant - Additional class crated to separate orders received from participants from car's logic.

The sequence of events in the main loop of the simulation was as shown in Table 2. While Simulation object hold supervision role over whole process, the Map object was responsible for the majority of tasks. Once Simulation received information from Agent application and passed it to Map, most commands were called on the basis of Simulation object asking Map object to do certain things and return some value which was then

Simulation Server Application	**Communication Agent**	**Client(s) Application**
Starting ROS Core and opening UDP ports for Clients and Agent	Connecting to ROS node and opening UDP ports	Connecting to ROS node and opening UDP ports
Setting up simulation parameters	Listening to instructions from Server...	Listening to instructions from Server...
Sending configuration messages to Clients	Listening to instructions from Server...	Receiving configuration messages from Server
Sending start order to Clients and Agents. Starting main loop	Starting main loop	Starting main loop
Main loop		
Sending individual messages to each Client	Sending combined orders from all clients to Server	Sending order to Agent
Receiving combined orders from Agent	Trying to receive from every client one by one	Receiving my location and vehicles' around me
Performing all calculations for clients, map and autonomous cars	Combining orders from all client to one message	Performing calculation and drawing map in viewport
Waiting for next loop iteration	*Waiting for next loop iteration*	*Waiting for next loop iteration*

Table 1: Simplified order of events across all applications. The order of the events in Agent resulted in one frame delay between giving order by Client and receiving it by Server.

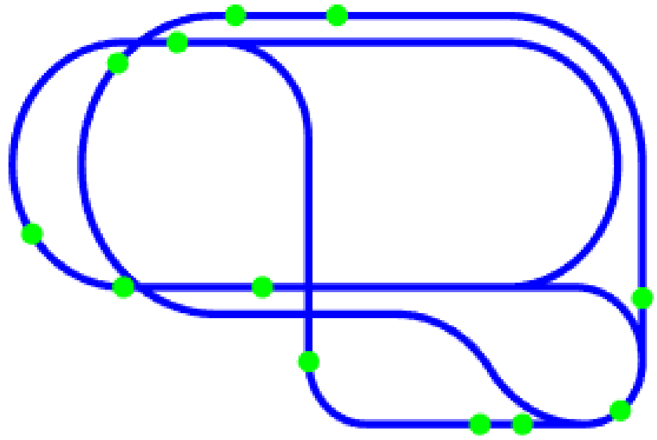

Figure 4: Visualization of current simulation status available via Simulation Server GUI. This example shows third map with 14 autonomous cars.

passed to e.g. Autonomous Car. An additional feature of Map class was an ability to create large raster images of whole track. These images were later used by Client Application.

Server Graphical Interface In order to simplify simulation control and supervise simulation status a server-side graphical interface was created. It's two main functions were displaying position of each car on the map and setting up each scenario configuration. Figure 4 shows top down view of the whole map available in the GUI. The interface capabilities were allowing to start ROS node, open UDP ports, choose number of cars of each type, choose map, send configuration messages to other parties and start or stop simulation.

Centralized control Running synchronized processes on multiple machines was a significant challenge and a source of potential problems. While the details of network communication are described later, additional, high-level measures were taken to simplify simulation management. The messages send between machines were always in the form of formatted strings. Throughout entire simulation Clients and Agent were always listening to messages broadcast from Server. This allowed to manage the simulation from Server

	Class	Event
1	Simulation	Sending each Client its location and orientation together with information about surrounding vehicles.
2	Simulation	Receiving message from Agent containing movement orders from all Clients
3	Simulation	Extracting orders from each individual Client
4	Simulation	Passing updated cars' movement orders to Map object
5	Map	Predicting position of all cars up to 3 seconds ahead based on current velocity and movement order
6	Map	Calculating collisions for current time and predictions made in last step
7	Map	For each autonomous vehicle finding potential collisions with other vehicles
8	Autonomous Car	Making decision on desired acceleration on the basis of information supplied by Map
9	Human Car	Calculating target acceleration on the basis of received acceleration order
10	Car	Calculating traveled distance using 4th order Runge Kutta equations
11	Map	For each vehicle calculating new position and edge on map topological structure
12	Map	For each vehicle calculating new Cartesian coordinates and orientation
13	Map	Preparing individual messages for each Client
14	Map	Drawing all vehicles on the map in Simulation Server GUI
15	Simulation	Saving simulation state at current step.
16	Simulation	Waiting for next loop iteration

Table 2: Order of events in main simulation loop in Simulation Server.

without any additional configuration on each single computer. There were two basic types of messages: configuration messages starting with letter 'c' and current simulation messages starting with letter 'm'. Configuration messages were usually sent outside of the main loop and contained informations about next simulation session such as map size, map name, initial location of vehicle. These message were also used to start or stop the simulation. To identify the message the first letter was followed by 3-digit code that was understandable for both parties. An example of map size configuration message is shown below.

$$c \quad 108 \quad 0 \quad 360 \quad 0 \quad 260 \tag{1}$$

First number 108 meant that map size is being sent. Rest of the message was then interpreted as x and y dimensions of the current map. Current simulation messages were often more complicated. Below is an example of message send from master to client in running simulation.

$$m \quad 124.56 \quad 189.70 \quad 43.1 \quad 10.8 \quad 1 \quad 2 \quad 141.5 \quad 164.9 \quad 56.2 \quad 135.5 \quad 150.4 \quad 66.8 \tag{2}$$

First 3 numbers meant car's location and orientation. Next two numbers indicated current speed to be displayed on speedometer and binary collision status (Participants were informed when collision occurred). Yet another number indicated how many other cars are in the surrounding. All numbers that followed described these cars' locations and orientations. That data was then used by Client to draw map and all vehicles in the view field. If message was received distorted or incomplete and therefore different from what was expected, it was rejected and values from previous iteration were used.

3.2.4 Client Application design

Identical copy of Client Application was deployed on each computer used by experiment participants. Main tasks of Client Application included receiving location and orientation, sending acceleration and turn order, displaying part of the map to the participant and harvesting inputs from keyboard. Its design consisted of following classes (appendix: class diagram):

	Class	Event
1	Simulation client	Sending acceleration and turn orders to Agent
2	Simulation client	Receiving locations and orientations from Server
3	Simulation client	Displaying speed and collision status on GUI
4	Map client	Cropping and rotating map image
5	Map client	Displaying cropped map image in viewport
6	Map client	Overlying cars on the map
7	Simulation client	Waiting for next loop iteration

Table 3: Order of events in the main simulation loop in Simulation Client.

- Simulation client - Main class. Responsible for communication with Server and Agent and management of whole simulation from client's side.
- Map client - The most important class. Responsible for such essential tasks as displaying the map and cars in GUI
- Car client - Relatively simple class containing some essential parameters of the car.
- Participant - Identical to the class used by Simulation Server Application. It contained some attributes that should be separated from Car client object.

The sequence of events happening at each loop iteration is shown in Table 3. As it can be seen, it was considerably simpler than Server Application.

Displaying map in view port Displaying car's surrounding was one of the main challenges in the implementation of client's application. As discussed earlier, the experiment design required showing a top-down view of a rectangular area around the car together with car itself and all cars contained in the view port. From the beginning of design process two, radically different approaches to achieve this goal were analysed. First idea was to calculate coordinates of each point required to render scene and display the results using one of MATLAB plot functions. This approach would allow for full scalability and could potentially result in appealing map image without visible pixels. On the other hand the amount of calculations could be much greater as not only cars and road were to be computed but also multiple stationary objects around the road that were suppose to improve the felling of speed (such as trees or houses). The second idea for the representation of view port was to crop and rotate part of the map stored as a large, raster image. The map image was suppose to be 2 to 5 thousand pixels wide and at each loop iteration a part of it would be cropped and rotated according to current car's location and orientation and then showed on client's GUI. Subsequently all vehicles would be plotted over the image. The main advantage of this approach would be a possibility to use complex map image which could be rich in diverse, colourful features. The main drawback would be less nattractive, pixelated image as the resolution would be limited. After initial trials with each approach, second one was chosen for implementation. As it quickly turned out, the main challenge was limited computational power of machines used in experiment. One iteration could not last longer than 0.0625 s and preparing map image was only one of the tasks that had to be executed (the frame rate was limited from 20 FPS in later stages of implementation due to Server Application performance reasons). To overcome this problem a custom function to crop and rotate was written. It was used instead of MATLAB methods *imcrop* and *imrotate*. The backbone of this function was written by project supervisor, Eddie Wilson. It was later adapted according to the requirement of the GUI. Once the cropped image was displayed on the GUI, vehicles were plotted over it using MATLAB *patch* function. The overall performance of this solution was sufficient for the needs of the experiment. It allowed to display images 480 pixels wide and tall with plenty of room left for remaining tasks.

Harvesting inputs form participants - maybe actually put it in car control

Client application was used to communicate with experiment participant

Client application was responsible for receiving

Client application was responsible for two-way communication with experiment participant. Each participant used exact same copy of client application.

DRAFT

It was tried to mimic the way cars are controlled in popular computer racing games such as Need For Speed^{TM}.

The behaviour of cars controlled by humans

here combined technical solutions

General description Simplifications and yet still accounting for most important parts of the car model

3.2.5 Human-driven Car control

The way in which cars were controlled had significant impact on the experiment results. From participant's point of view car's behaviour should be predictable and similar to how real car behaves. The challenge was to achieve this kind of performance using only discreet inputs from keyboard. Graphical interface used by participants allowed to capture multiple keys pressed simultaneously, however resulting acceleration order had to always be one of the following: speed up, slow down, coast or brake. After analysing relevant literature it was decided that car's behaviour should be similar to one of the cars following models (Treiber & Kesting 2013). From The Gipps' Car Following Model given in Spyropoulou (2007) a formula describing acceleration on the basis of current speed was extracted.

$$\dot{v} = 2.5a(1 - \frac{v}{V})\sqrt{0.025 + \frac{v}{V}} \tag{3}$$

In the above equation v is current velocity, $\dot{v}$ is acceleration available at current speed, a is acceleration parameter and V is velocity at which car should not be able to accelerate any more.

Value of a was found empirically to be 5. Figure 5 illustrates how the acceleration value depended on the current velocity. Gipps' model was used only when participant's order was to accelerate (A key). When the order was to slow down (Z key) the applied value of acceleration was $-6.5\,{}^{m}/_{s^2}$. While coasting the acceleration value was 0. To imitate car's dissipating energy coming from aerodynamic drag and rolling resistance the calculated value of velocity was brought down by 0.5% in every loop iteration; This principle applied also to autonomous cars. Last available command influencing car's velocity was braking (SPACE bar) which gave an acceleration of $-10\,{}^{m}/_{s^2}$.

As the experiment was dedicated to city traffic the maximum velocity of traditional vehicle was limited to 15 m/s. Starting from full stop and heaving acceleration button pressed the car would reach that velocity after X(?) seconds.

show speed/time with full acceleration - compared to autonomous car (or maybe put comparison in autonomous car section)

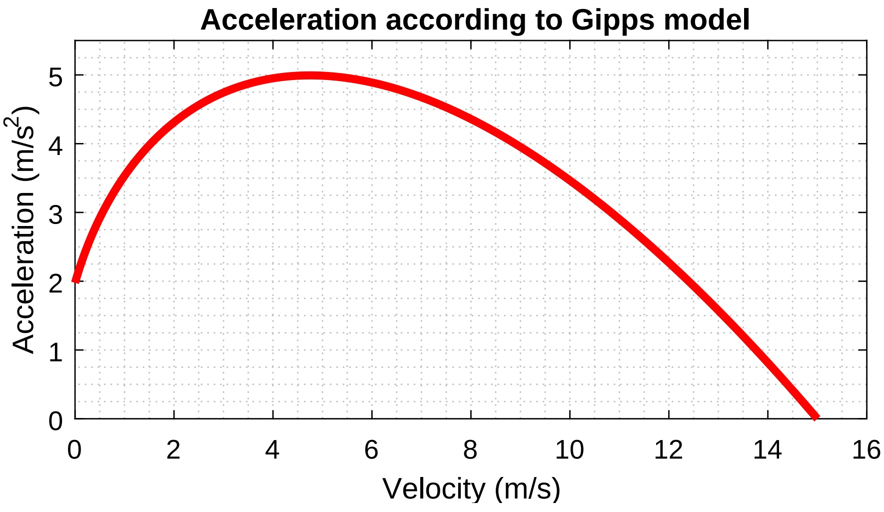

Figure 5: Available acceleration value depending on the current speed.

graph of coasting...in time or distance travelled - speed vs time?

gave relatively .

However, unlike real car the model used in the simulation

Parameters were optimized to give possibly most realistic feeling of car control NFS

The challenge was to

In real car the acceleration is controlled by analogue throttle

gipps graph here. reference to book or paper?

3.3 Communication between machines

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From one point of view this a tightly coupled with software development but the way communication was established doesn't matter from the point of view of software structure. Simply speaking the comms should only meet some requirements derived from the main piece of software and the details of implementation doesn't matter. This was a significant part of the job and its an achievement on its own.

3.4 Autonomous Car algorithm and comparison with human-driven Car

DRAFT

Say why this is important from the point of view of results obtained. Again justify all design decisions

add Examples of autonomous cars behaviours from experiment.

say about main flaws

comparision:

kutta: velocity/time when acceleration is pressed - one graph comparing human and autonomous vehicles

another similar one for breaking - actually two lines for human car(1 types of braking) and one line for autonomous...?? how to establish this

maybe these graphs could be actually not only velocity but also acceleration and distance travelled

seperate chapter for comparrision

4 Findings and results

The experiment took place on the 24th of August 2016. 12 people people turned up for the experiment. The group was divided into 2 smaller groups of 6 people each. Once first group completed all tasks, another one was asked to begin. The reasons to split people into two groups were of technical and research nature. A technical problem arose shortly before the experiment was due to to start. It turned out that from participant point of view the simulation gets considerably laggy if there are more that 7 people playing at the same time. The original frame rate was dropping to few frames-per-second which was unacceptable as it would greatly distort the simulation and whole experiment.

From the point of view of experiment methodology heaving two groups conducting identical tasks had beneficial impact on the conclusions that could be drawn from the experiment. It is a common practice to run experiment more than once to detect potential anomalies and have more generalized data(here use Design and Analysis of Experiments," Handbook of Statistics book).

4.1 Experiment execution

Experiment was advertised as ”Autonomous Cars Simulation”. Invitations were sent privately to particular persons. The only information revealed to potential participants stated that experiment will consist of a couple of sessions and they will be asked to drive a car in computer simulation. Participants were promised £10 reward in form of Amazon.com® voucher and catering available before and after the experiment.

Each of the participants was asked to sit in front of one of selected computers. In front of them there were 3 documents: Consent Form, Participation Information Sheet and Questionnaire. (link to appendixes) ...?

4.1.1 Questionnaire

Each of the participants was asked to complete short questionnaire. (link to appendixes). The purpose of the questionnaire was to collect data that later could be used in association with experiment results to create a driving profile for particular person. The exact way in which this data will be used in analysis was not established before the experiment. None the less, it was attempted to ask about things that could be associated with performance of each person.

The survey consisted of 12 questions which can be divided into 4 sections. There were 2 questions asking about gender and age. Next it was asked whether a person played any racing computer games and is familiar with controlling the car with arrow keys. The third section was conditional to the possession of driving licence. If the answer was affirmative, further questions asked about past accidents, subjective evaluation of person’s driving style and irritating behaviours they encounter of the roads. Last question asked about opinion on how the traffic will change when autonomous cars are introduced.

4.1.2 Minutes

The experiment started by reading the Participation Information Sheet to all participants. First paragraph stated rights of experiment participants and how the collected data will be used. Second one explained the task in short and concise way. The exact instructions that were given stated as follows:

”If you decide to take part in the study, you will be asked to drive a car in on-line traffic simulation. You will be using computer keyboard to control your car. Your main objectives is to cover as long distance as possible and avoid crashing into other cars. There will be 3 phases. Each will last 8 minutes, feature different map and different amount of autonomous vehicles. First phase will be preceded with 3-minute- long learning period when you will be able to learn how to play the game. All additional instructions will be given to you before each phase in form of power point slides. Before starting the simulation you are asked to complete a short survey to describe your driver profile.”

Rest of the document considered health warnings such as epilepsy and past accidents. Next, participants were asked to complete the Questionnaire described above and sign the Consent form. Once that was done they were told once again what is their task, how to control the vehicles and what the next phase will look like. Eventually the main part of the experiment commenced. It consisted of consecutive phases as described it table 4.

Phase	Scenario	Human-driven vehicles	Autonomous vehicles	Lenght
Group 1				
Learning	Learning	6	1	1:45 min
1	Scenario 1	6	1	3:22 min
2	Scenario 2	4	3	4:12 min
3	Scenario 3	4	4	4:09 min
Group 2				
Learning	Learning	6	1	4:33 min
1	Scenario 1	6	1	4:07 min
2	Scenario 2	4	3	5:03 min
3	Scenario 3	4	4	4:51 min
4 (additional)	Scenario 3	6	4	2:24 min

Table 4: My caption

The lengths of each phase were considerably shorter than planned. The initial schedule, however, did not account for heaving two streams of people.

After the main part of the experiment finished, participants were debriefed and invited for catering. Entire experiment lasted around 1.5 hours and in total 31 minutes of simulation data were harvested.

4.2 Experiment results

...another sentence here The analysis of the data could be divided into two parts. First one is dedicated to finding patterns, observing dependencies and evaluating particular group and participants. Second one proposes a range of hypotheses which were consequently tested with proposed methods against the data collected. The discussion of the results was placed in next chapter.

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Data collected during the experiment was considerably rich in features and lots of regularities could be potentially found. On average participants changed acceleration/deceleration commands 73 times per minute. Figure 6 shows a snapshot from simulation playback.

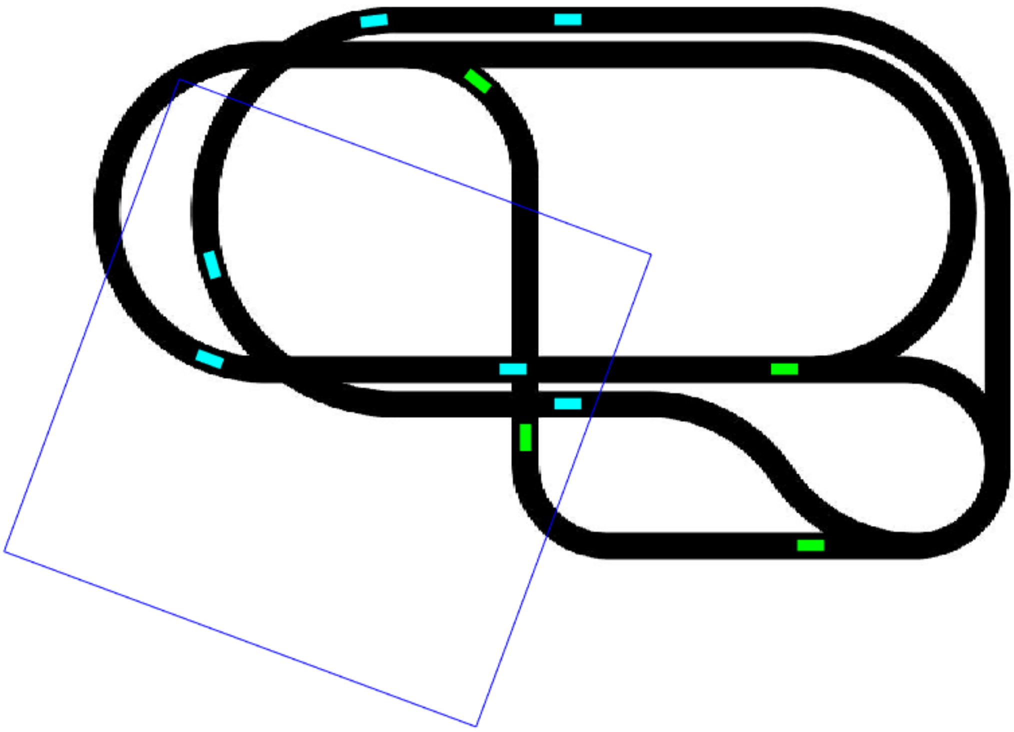


Figure 6: Group 2, phase 3. A snapshot from simulation playback. Cyan colour represents human-driven cars and green represents autonomous cars. A dark blue rectangle represents the view field for one of the cars.

Initial choice of parameters measured across data set was different from what different from what was calculated in the process of data analysis.

4.2.1 Observations

some text here

Decelerations mapping

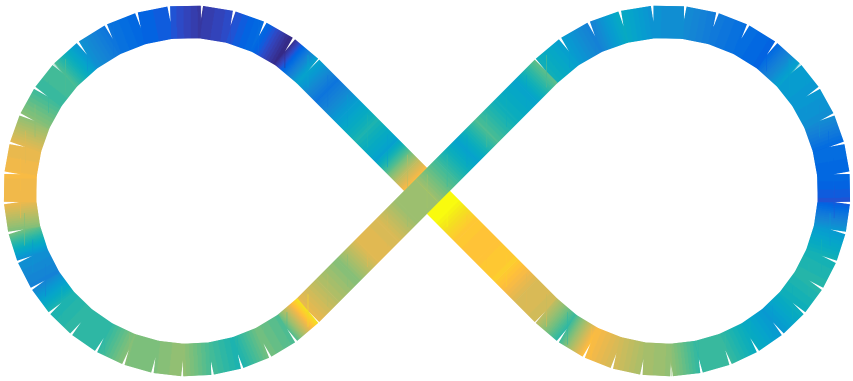
First idea that could help to understand the data was to visualize how vehicles accelerated and decelerated. In order to do that a spatial representation of average decelerations was created as it it shown of Figure 7. Track was divided into 4-meters-long segments and for each segment total value of decelerations was summed up over all vehicles and all frames in current phase. Results were plotted for first and second scenario for group 1.

It can be observed from the plot that once multiple autonomous cars were introduced, vehicles decelerated harder and more often when approaching the intersection.

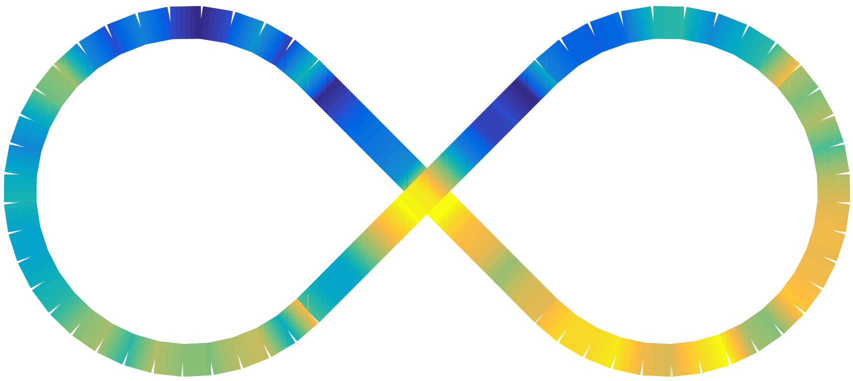
Evaluation of participants' performance

Number of collisions caused by each participant was evaluated and compared against questionnaire responses. Single collision always involved 2 cars. A person responsible was always the one whose car front line intersected the other car first. A number of collisions caused by each person is shown on Figure 8. Table 5 shows number of collisions against questionnaire responses. Becouse the shorters phase lasted 3:22 minutes, values were calculated only for that period for all phases. From these figures it can be seen that:

- Almost every person in the first group performed significantly better in terms of number of collisions than participants from the second group. Because of this reason first group was used more often in further analysis as a sole source of data.
- Autonomous cars were responsible for only one collision throughout entire experiment.
- In total 52 collisions occurred between two human drivers while 33 happened between human drivers and autonomous vehicles. However, accounting for how much



(a) Group 1, Scenario 1



(b) Group 1, Scenario 2

Figure 7: Visual representation of decelerations on map used in first and second scenario. Dark blue represents strong deceleration while light yellow represents weak deceleration. The data was averaged over all vehicles including human-driven and autonomous one.

each vehicle spent on the track .... ?

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HH and HA collisions..?

In order to decide who was responsible for

Performance of each participants was evaluated on the basis of

Heaving two groups of people allowed to find potential anomalies..

asses every participants:

Partici-pant	Familiar with keyboard car control?	Years of driving experience	Past accidents	Driving skill evaluation*	Driving style**	Collisions (H/A)
Group 1						
1	Yes	2	0	2	Very careful	**1/2**
2	Yes	1	1	8	Careful	**4/2**
3	Yes	5	0	8	Normal	**0/2**
4	Yes	6	0	9	Careful	**2/2**
5	Yes	5	2	7	Careful	**3/1**
6	Yes	2	2	10	Normal	**2/0**
Group 2						
1	Yes	No licence	-	-	-	**11/5**
2	Yes	3	1	9	Normal	**7/6**
3	Yes	8	0	8	Careful	**4/5**
4	Yes	15	3	10	Normal	**8/5**
5	Yes	8	2	8	Agressive	**5/1**
6	Yes	3	0	1	Very careful	**4/1**

Table 5: Questionnaire responses represented against number of collisions caused by each person. It can be observed that self-assessment of driving did not correspond to the number of accidents. (*Own judgement of driving skills on the scale from 1 to 10. **Own judgement of driving style from very careful to very aggressive. Please refer to appendix for details.)

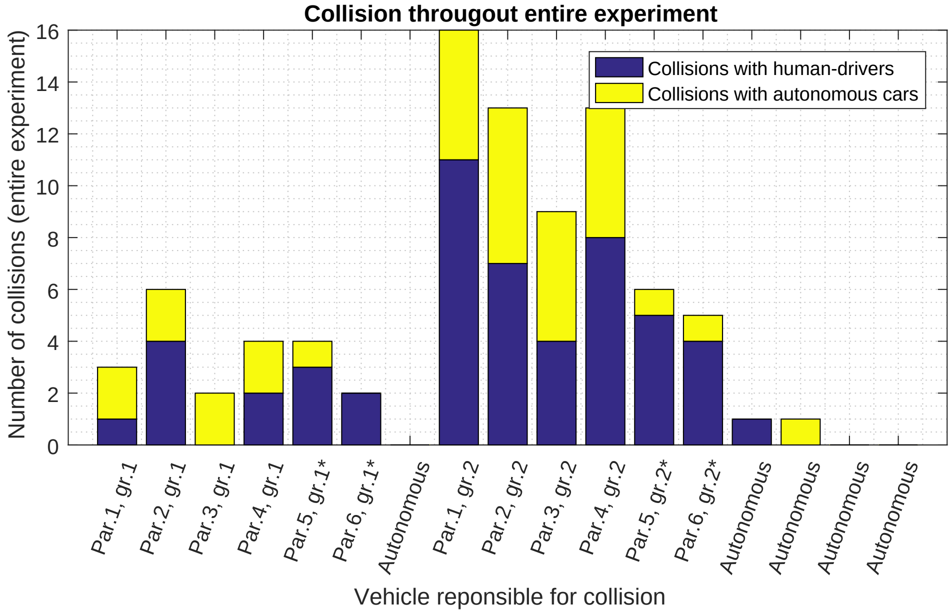

Figure 8: Number of collisions caused by each participant/vehicle in first and second group. (*Humans substituted for autonomous cars in later phases.)

Conflicts resolution

Interactions between cars can be systematized as one car following another or as a broad range of interactions at intersections. The later was of particular interest because of it's uncertainty and unpredictability. While all maps featured intersections, figure of eight map used in first two scenarios was aimed at more organized analysis and will be used in this example to visualize how humans and autonomous cars made decisions. Figure 9 shows an example of interaction between one human-driven and two autonomous car. In this example both vehicles at the front came to full stop. In ideal situation one vehicle should pass while the other slows down.

DRAFT

//something on conficts reosultion: some paper/ nash equlibrum

//some paper on interaction between autonomous cars

Another type are interactions between two autonomous cars as it is shown on Figure 10. When two autonomous cars anticipate collision with each other the one which is slower is ordered to reduce its speed according to the time-to-collision value while the faster one passes through uninterrupted. In most cases this relatively simple rule opti-

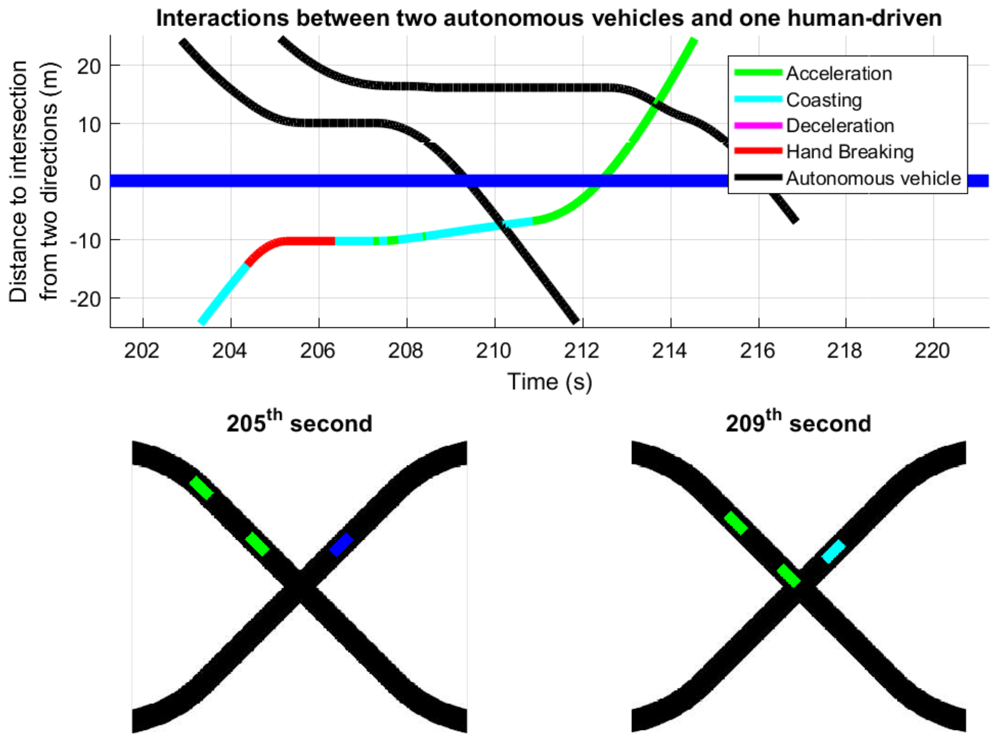

Figure 9: An example of interaction between two autonomous vehicles and one human-driven. In 204th second both cars started to brake to avoid collision and came to full stop. Human driver was uncertain of how the other car will behave. Autonomous car, on the other hand calculated collision free passage as other vehicle was not moving and starter to move through the intersection in 208th second. Next, human passed through and another autonomous vehicle afterwards. (Colours indicate current order from Participant.)

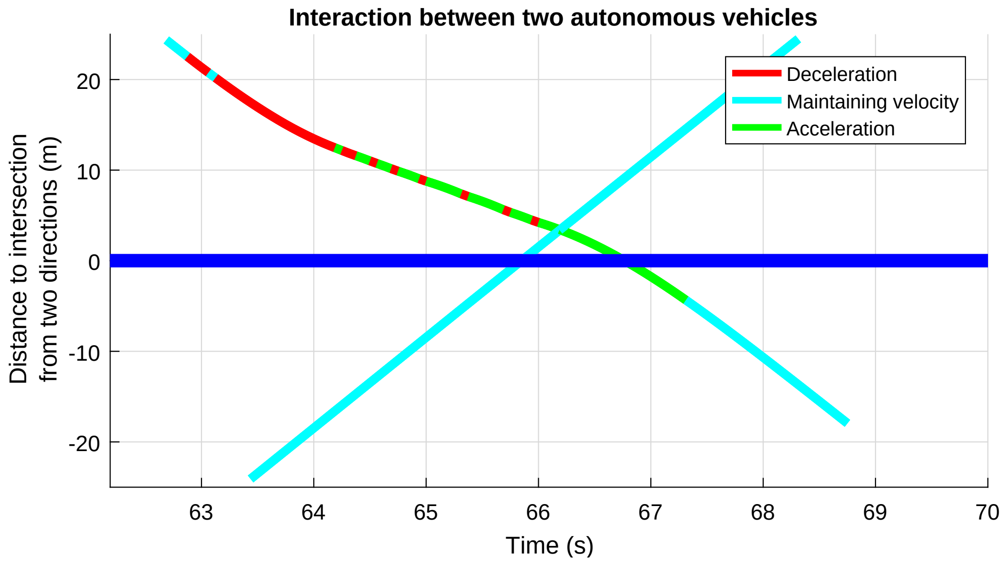

Figure 10: An example of interaction at the intersection between two autonomous vehicles coming from different directions. Both cars anticipated collision in 65^{th} second. In line with the algorithm the slower car started to decelerate as much as it was needed to avoid collision. At each time step new time-to-collision was calculated and velocity adjusted accordingly. The faster car's velocity remained constant.

mizes the interaction reducing braking to minimum.

//figure of autonomous cars

Reaction times

Another topic of interest were reaction times of both types of vehicles. It was anticipated that the rule to always let human driver pass first and potentially faster reaction by autonomous car would have beneficial impact on the traffic. Particular interest was in differences between reaction times of humans and autonomous cars.

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//use third map here...

sth else

also exmaple of two autonomous cars and two human drivers

part 1: observations: some interesting graph but no broad idea what for :D

-evaluate group (in terms of number of accidents, questionnaire responses) and which group were in general better - that will justify why you use one group more often

-

- heatmap of accelerations in figure of eight for two phases...and two groups? also scenario 3

scenario 1 and 2 (from different groups): - your nice graph with lines for some h-h, a-a and h-h situations - eddie's graph for some other situations (or the same)

-reaction times of each driver

part 2: hypothesis

approach to analysis: hypthoseis

4.2.2 Hypothesis: Autonomous cars reduce number of accidents

Based on the observations from previous section it can be seen that autonomous vehicles were almost never responsible for collisions. However, there were numerous collisions caused by other traffic participants involving autonomous cars. Based on these premises the following hypothesis was be tested:

"Replacing part of traditional drivers with autonomous cars reduces number of all kinds of accidents"

Method of analysis The hypothesis was tested by comparing number of collisions in phase 1 and phase 2 in both groups of participants. In order to ensure validity of the results an attempt to identify all factors influencing number of collisions was made. As a result a list presented in Table 6 was created.

According to Vangi & Virga (2007) the deceleration of an average car (Renault Clio®) in good driving conditions, from the speed of $15 m/s$ reaches maximum of $12 m/s^2$. Although this value might be greater for cars with better brakes it was accepted as a border value. Any situation when deceleration of autonomous car was greater that $12 m/s^2$ was analysed separately to classify it as a potential collision.

Findings In first group there were 11 collision in first scenario and 5 collisions in second scenario. In both scenarios there were 3 situation where deceleration of autonomous vehicle reached values below $12\ m/s^2$. None of them was classified as potential collision.

	Factor	Comment
1	Density of the vehicles.	In phase 1 and phase 2 total number of cars remained constant.
2	Participants improving their skills in vehicle control in consecutive phases.	This factor is hardly accountable for. Its influence was ignored in data analysis however, it was taken into consideration when drawing conclusions.
3	Initial placement of vehicles.	Placement of vehicles was constant through first and second scenario.
4	Length of each phase.	Data was compared over the same length for each phase.
5	The algorithm governing autonomous cars allows for large, unrealistic decelerations.	It was attempted to identify the frequency of these behaviours and its impact on traffic was accounted for.

Table 6: Factors affecting number of collisions.

In second group there were 37 collisions in first scenario and 14 collisions in second scenario. In the first scenario there were 6 situations where deceleration of autonomous car reached values below $12\ {}^{m}/{}_{s^2}$. None of them was classified as potential collision; In fact these rapid changes of velocity often caused collisions with the car behind which was unable to stop. This should be considered as a flaw in the design of autonomous car algorithm. In the second scenario in second group there were 3 situations where collision was likely prevented by abnormal deceleration of one of autonomous cars. Between first and second scenario number of collision in first group dropped by 55% and by 45% in the second group(including 3 potential collisions). Therefore the following conclusion might be drawn:

Substituting traditional cars with autonomous ones reduces overall number of accidents.

Remarks

- The statement should be verified in further research by accounting for factors mentioned in Table 6.
- Large number of collisions with autonomous cars in third scenario leads to assumption that algorithm governing autonomous cars does not perform satisfactory on more complicated map.
- Differentiating head-on collisions from all other collisions could have impact on the results.

4.2.3 Hypothesis: Autonomous cars smoothed out traffic

All interactions can be segregated into 3 different types: autonomous-autonomous, human-autonomous and human-human. As it was shown before, interactions between two autonomous cars are usually highly optimized. On the other hand, interactions between two humans are random and uncertain by its nature. The third type of interactions involving both human and autonomous vehicle can potentially contain some level of systematicity and yield better results than solely human drivers. On the basis of these premises the following hypothesis was suggested:

Parameter	Scenario	Group 1 (4 humans)	Group 2 (4 humans)	Group 1 (all vehicles)	Group 2 (all vehicles)
Acceleration variance	1	9.61	12.09	9.14	12.00
	2	7.85	11.39	5.24	8.01
Velocity variance	1	24.70	33.83	24.13	30.56
	2	25.09	29.45	21.37	22.07

Table 7: Average acceleration and velocity variance calculated separately for 4 participants (who took part in both scenarios) and for all vehicles in particular scenario. In can be seen that speed and acceleration variance for humans did not change much between two scenarios. However, when more autonomous cars were introduced the average variance for whole group dropped significantly.

Replacing part of traditional drivers with autonomous cars smooths out traffic (this is not very precise..sth about being start-stopy)

Method of analysis The main measure used to confirm or deny the hypothesis was calculating dispersion of velocities and accelerations for particular vehicles and comparing the results between different scenarios. ...(Dixon & Massey Jr 1957)

First parameter calculated was variance of acceleration. Figure 11 gives variance values for both groups for first and second scenario for particular vehicle. In a similar way variance was calculated for velocities it is shown on Figure 12. Next, mean variances were calculated for 4 people in each group who took part in both phases and independently for all vehicles in each phase. Results are summarized in Table 7.

Findings From one point of view the impact of autonomous cars is clearly visible - average variance dropped significantly. However, if only humans are taken into consideration the differences are considerably slighter. Acceleration variance declined by 18.3% for first group and by 5.7% for second group. Velocity variance in fact rose by 4.1% for first group and declined by 12.9% for second group. Additionally, accounting for the fact that people's driving skill improved each round the hypothesis can be only partly confirmed:

From the point of view of global traffic performance replacing part of traditional drivers with autonomous cars smooths out traffic since there are fewer human

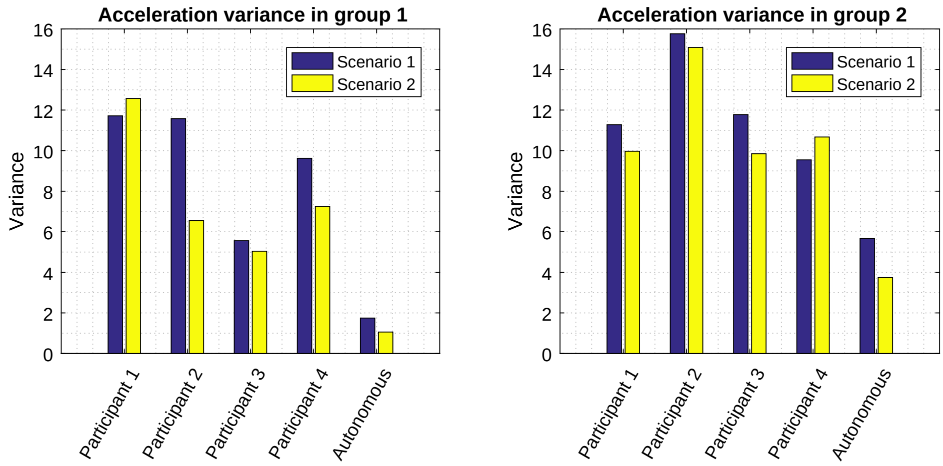

Figure 11: Acceleration variance values calculated for 4 participants that took part in first and second phase and 1 autonomous car. The obvious observation is that autonomous car's acceleration varies very slightly compared to any human driver. Another observation is that variance dropped for 6 out of 8 participants when autonomous cars were introduced.

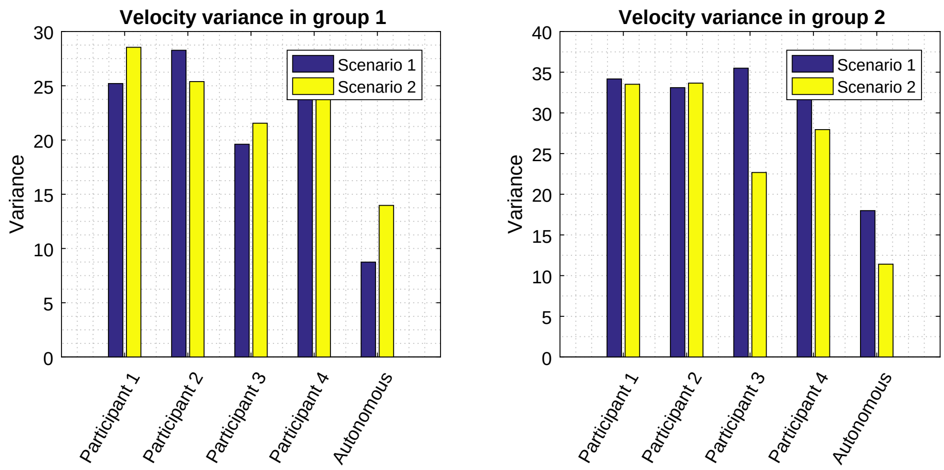

Figure 12: Velocity variance values calculated for 4 participants that took part in first and second phase and 1 autonomous car. Similar to previous figure the variance values for autonomous cars were lower than those of human. However, for human drivers hardly any pattern is observable between first and second scenario.

drivers who drive less systematically than autonomous cars. However, from the point of view of particular driver the presence of autonomous cars did not prove to have evident impact on driving smoothness.

4.2.4 Hypothesis: Most efficient traffic could be achieved with solely autonomous vehicle

According to (paper) most benefits of autonomous cars will be experienced only when human drivers will completely disappear from roads. In previous section it was shown that autonomous cars exhibit highly efficient interactions with each other. In line with these examples very good traffic parameters should be observable for simulation involving only autonomous cars. The following hypothesis was proposed:

For traffic consisting solely from autonomous cars parameters such as: total distance covered, acceleration variance and number of collisions should improve in comparison to traffic consisting of both types of vehicles.

Method of analysis In order to evaluate the hypothesis a simulation on map used in first and second scenario with 7 autonomous cars and no human drivers was conducted. Apart from measuring parameters mentioned in the hypothesis it was checked whether any kind of equilibrium is reached for this particular shape of the track. In addition to this, trials with different densities of vehicles were made using map from the third scenario.

Findings A trial run on the map from first and second scenario showed there were no collisions at all. Total distance covered by all cars was 13.4 km. For first group this value was 11.27 km in first scenario and 9.96 km in second scenario. Therefore autonomous cars travelled further even though their velocity was limited to $10\ ^{m}/_{s}$ which was 33% lower than what human-driven cars were capable of. Average variance on acceleration was 0.7850 which was 11 times smaller than the smallest value from scenario 1. Values for particular vehicles are shown on Figure 13. Next, it was investigated whether cars reach velocity equilibrium. The results showed that indeed equilibrium is reached after 1.5 minute (Figure 14). However, the worth of this measure can be little of none. The simulation was run on a closed track with no intersections and there was no randomization introduced at any point of the simulation apart form the initial placement of vehicles.

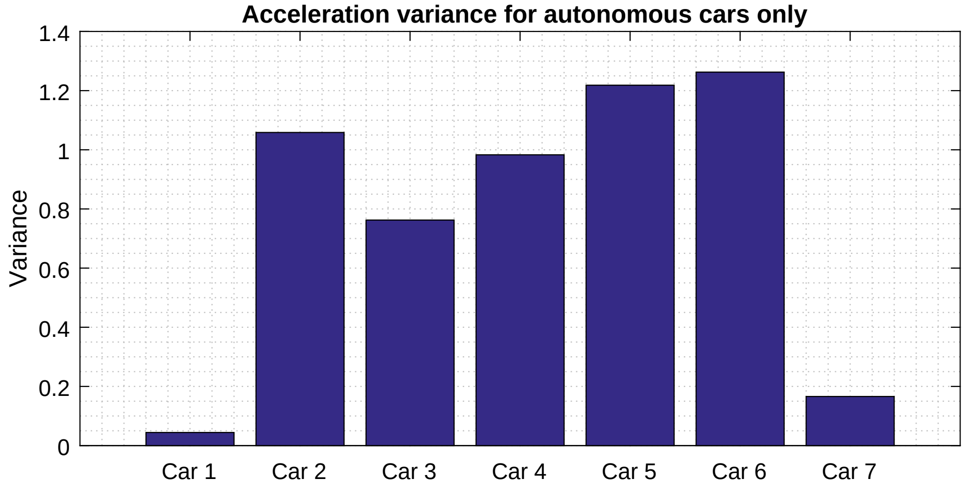

Figure 13: Variances of acceleration for simulation involving only autonomous cars. The values for each car were multiple times lower than in any trial with human drivers. Additionally cars 1 and 7 travelled with even less interruption. This is probably because their initial placement allowed to reach maximum speed before other vehicles. Consequentially they were always given higher priority at the intersection.

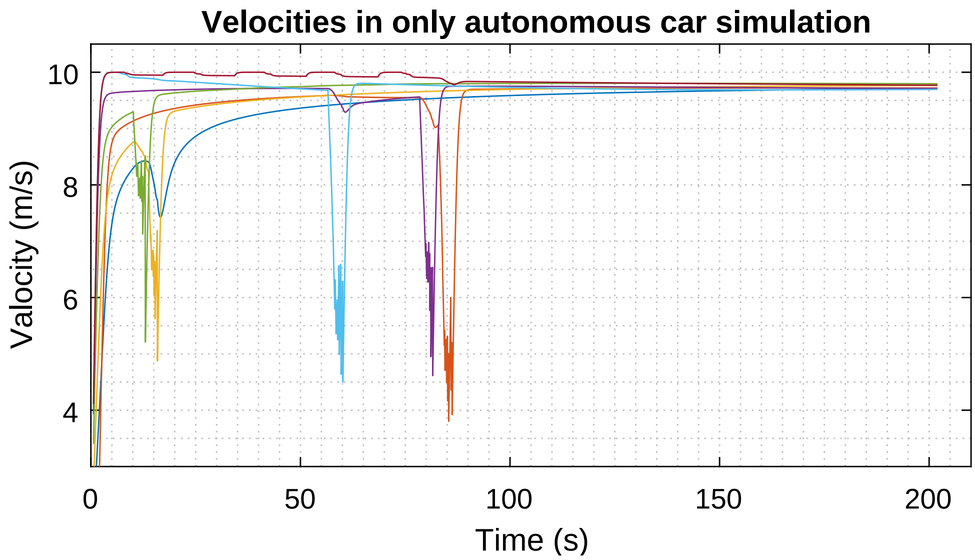

Figure 14:

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..write more about it...

what is the method and why it makes sense

- run trials with only autonomous cars. 7 cars on figure of 8 and 8 cars on scenario 3. Additionaly enlarge number of vehicles to maximum for figure of 8 (or scenario 3 too?) -find if velocity reaches some equilibrum..

when traffic will consist solely of them.

will be experienced only when autonomous cars become common and affordable

statement of the hypothesis Premise: autonomous cars show much more optimized reactions between each other compared to interaction h-h or h-a

4.2.5 Hypothesis: Interactions were better between two human drivers rather than human and autonomous

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statement of the hypothesis Premise: autonomous car algorithm make them always give way to humna driver if the collision is anticipated. However, if the human driver will also slow down it might be possible that autonomous car will not anticipate collision any more and will start to move. This can cause another

Method of analysis what is the method and why it makes sense

- run trials with only autonomous cars. 7 cars on figure of 8 and 8 cars on scenario 3. Additionaly enlarge number of vehicles to maximum for figure of 8 (or scenario 3 too?) -find if velocity reaches some equilibrum..

Findings Describe you you did and what you got as a results

5 Discussion(of results)

releta to questionaire reponses..?

relate to all hypotheses and say what the results actually mean.

6 Conclusions

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